Measuring the Neutrino Mass Hierarchy: Reactor Neutrinos

Dan Dwyer

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Outline

Reactor Neutrinos:

Signature of the Neutrino Mass Hierarchy

Measurement Approach

Challenges

Schedule and Prospects

Closing Statements

3-Flavor Oscillation

For reactor neutrino oscillation, vacuum expression is sufficient:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \overbrace{\sin^2 2\theta_{13}(\underbrace{\cos^2\theta_{12}}_{\sim 0.7}\sin^2\Delta_{31} + \underbrace{\sin^2\theta_{12}}_{\sim 0.3}\sin^2\Delta_{32})}^{\text{Daya Bay Oscillation (\sim km)}} - \overbrace{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}^{\text{KamLAND Oscillation (\sim 100 km)}}$$

Two oscillation frequencies

$$\Delta_{ji} = 1.267\,\Delta m^2_{ji}(eV^2)\frac{L(m)}{E(MeV)}$$

For both hierarchies:

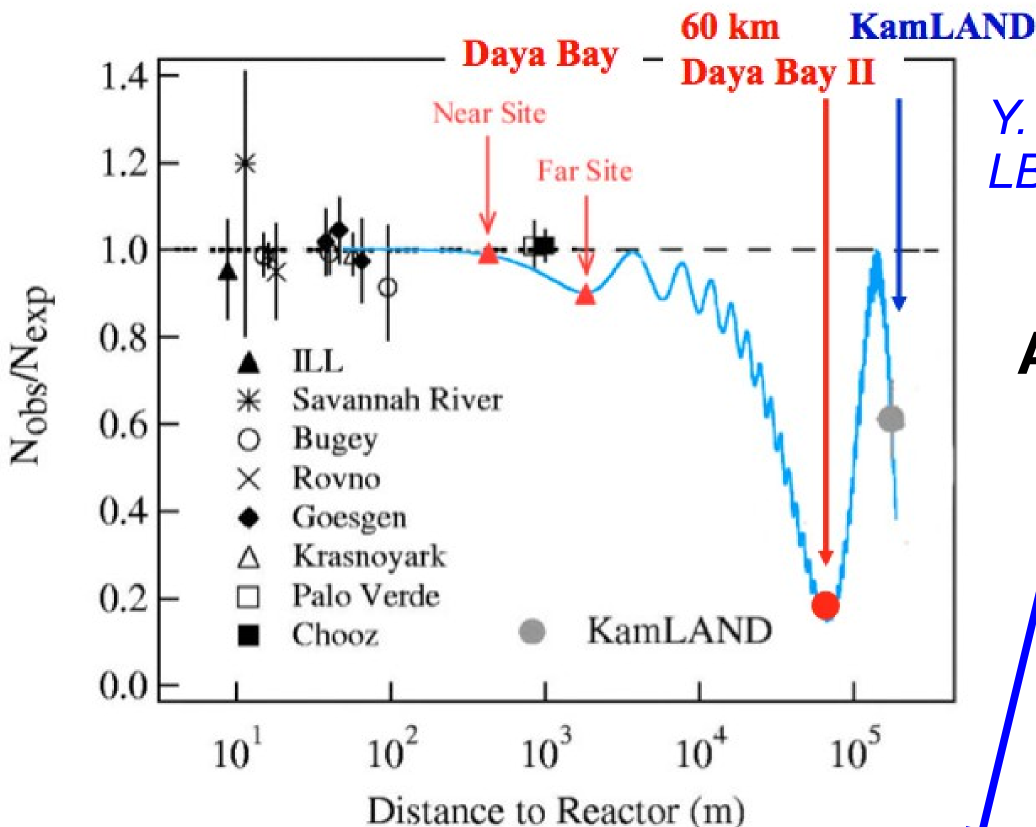
$|\Delta_{31} - \Delta_{32}| = |\Delta_{12}|$ → *Frequency difference give no hierarchy information*

But amplitudes are different:

Normal Hierarchy: $|\Delta_{31}| > |\Delta_{32}|$ → *Larger amplitude at higher frequency*
Inverted Hierarchy: $|\Delta_{31}| < |\Delta_{32}|$ → *Larger amplitude at lower frequency*

Proposed Experiments

??? (a.k.a. Daya Bay II) is the only planned reactor hierarchy experiment.



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At ~60 km from reactors:

Discrimination of two frequencies enhanced

Contribution from KamLAND term reduced

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Daya Bay II

'Super - KamLAND':
- 20 kT liquid scintillator detector
- >30 m diameter
- ~15000 20” PMTs (~80% coverage)

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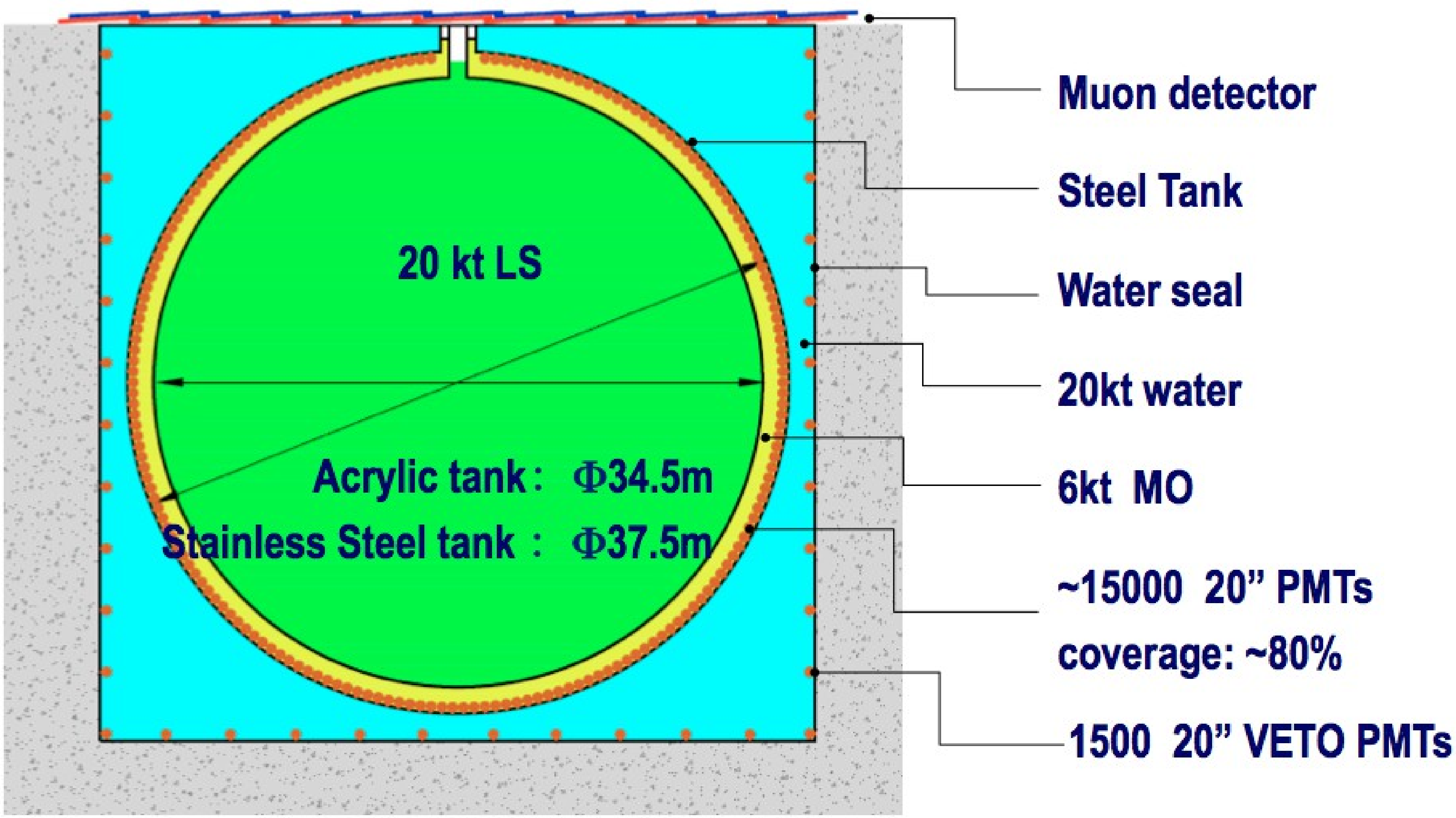


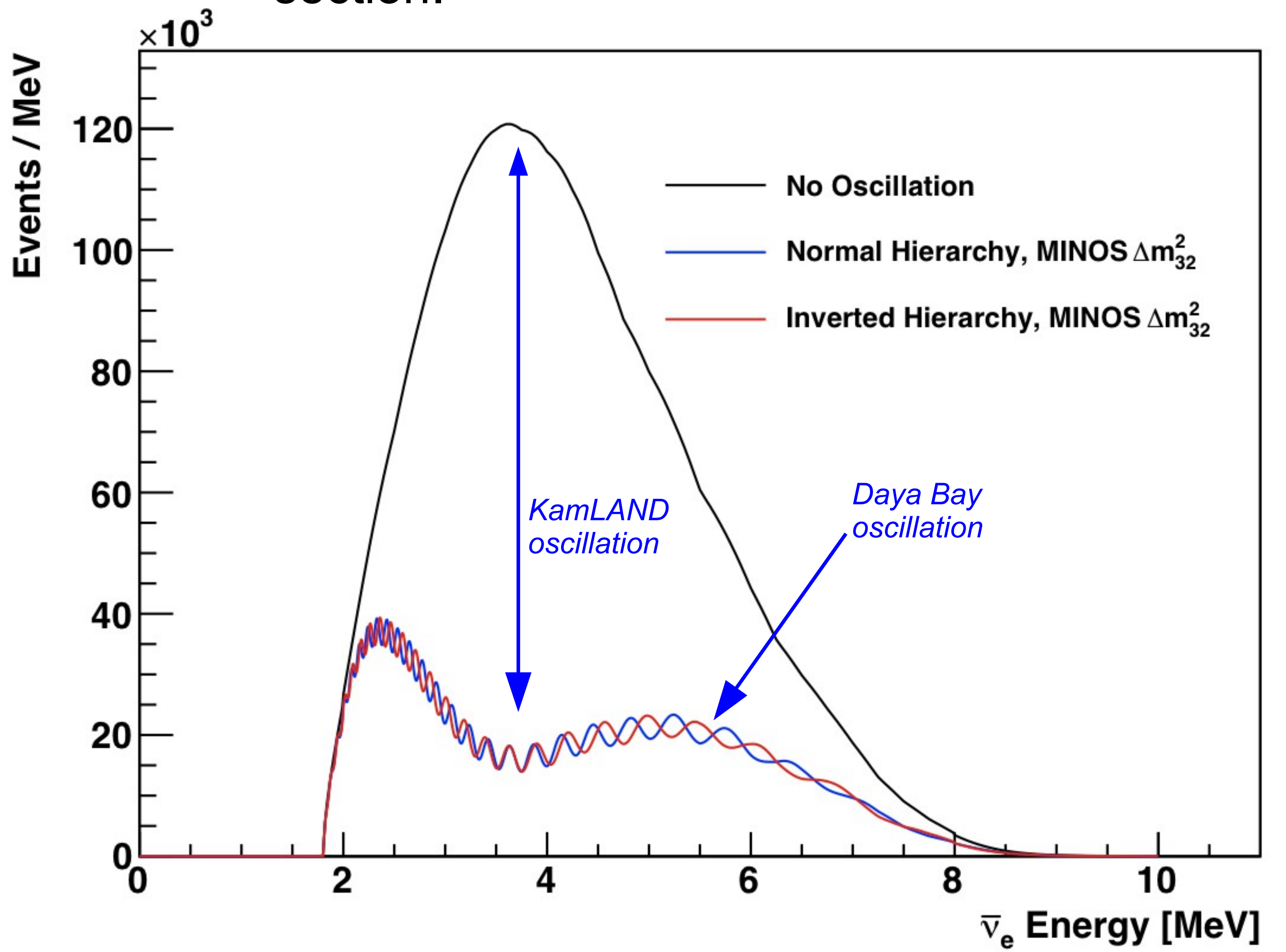
Expected Signal

Example Reactor Signal:

40 GWth reactor power
20 kT detector
58 km distance
5 year exposure

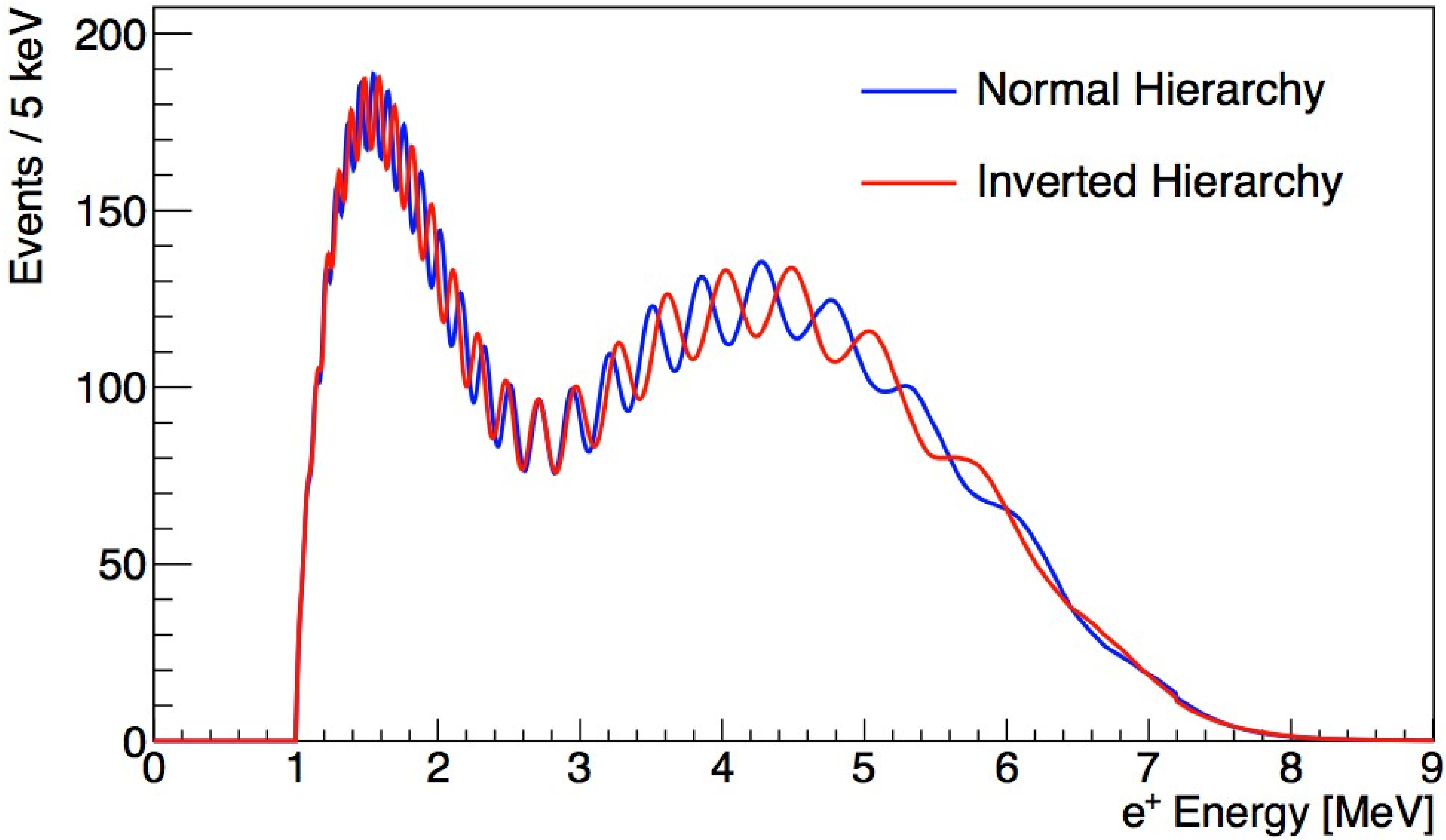
→ ~100k events
(with oscillation)

Reactor anti-electron neutrino spectrum, weighted by inverse beta decay cross-section.



Expected Signal

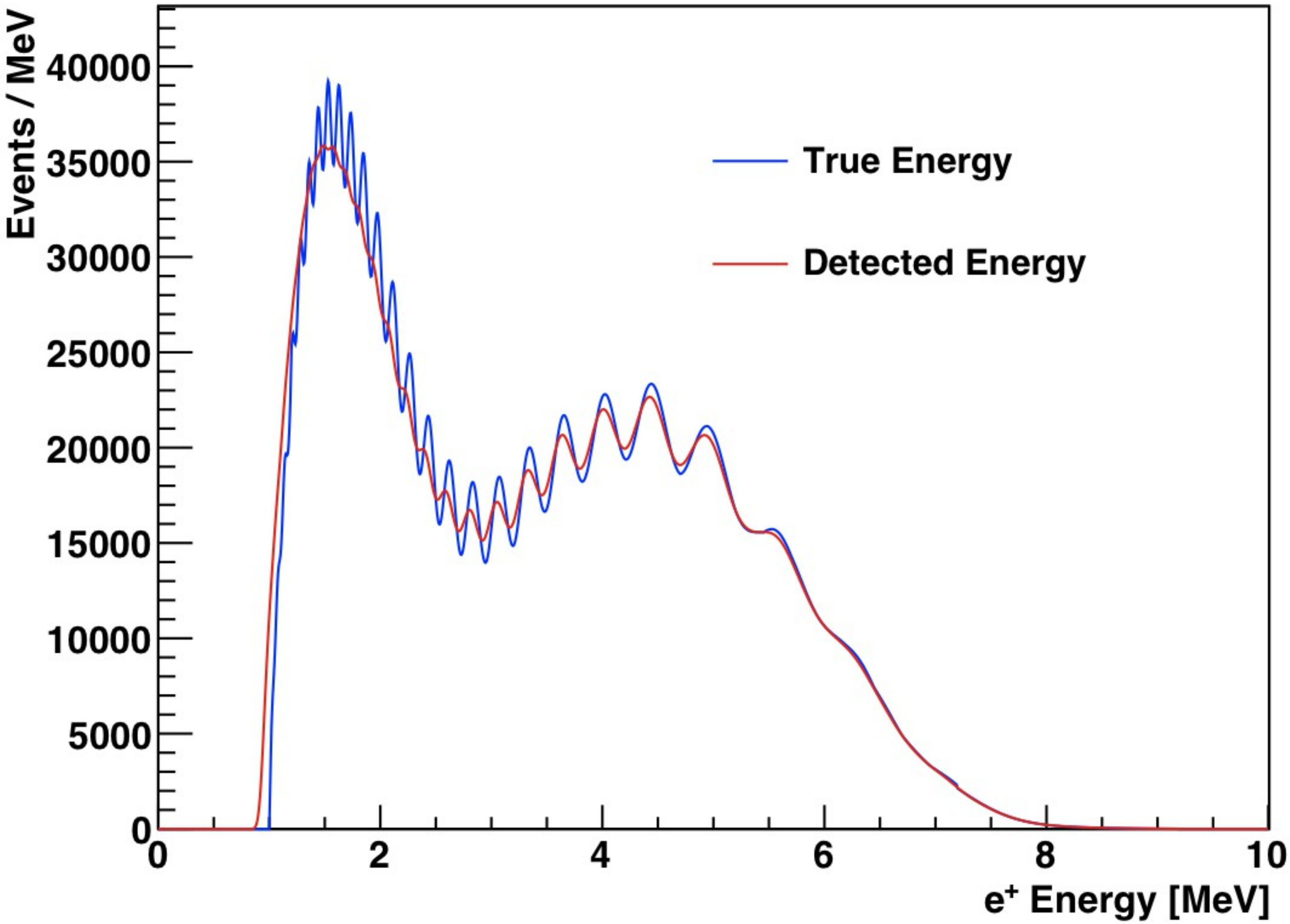
For a 'perfect' detector, hierarchy signal is obvious:



Positron from inverse beta decay preserves neutrino energy: $E_{e+} \approx E_{\nu} - 0.8$ MeV

Detector Resolution

High detector resolution essential to detect oscillation.



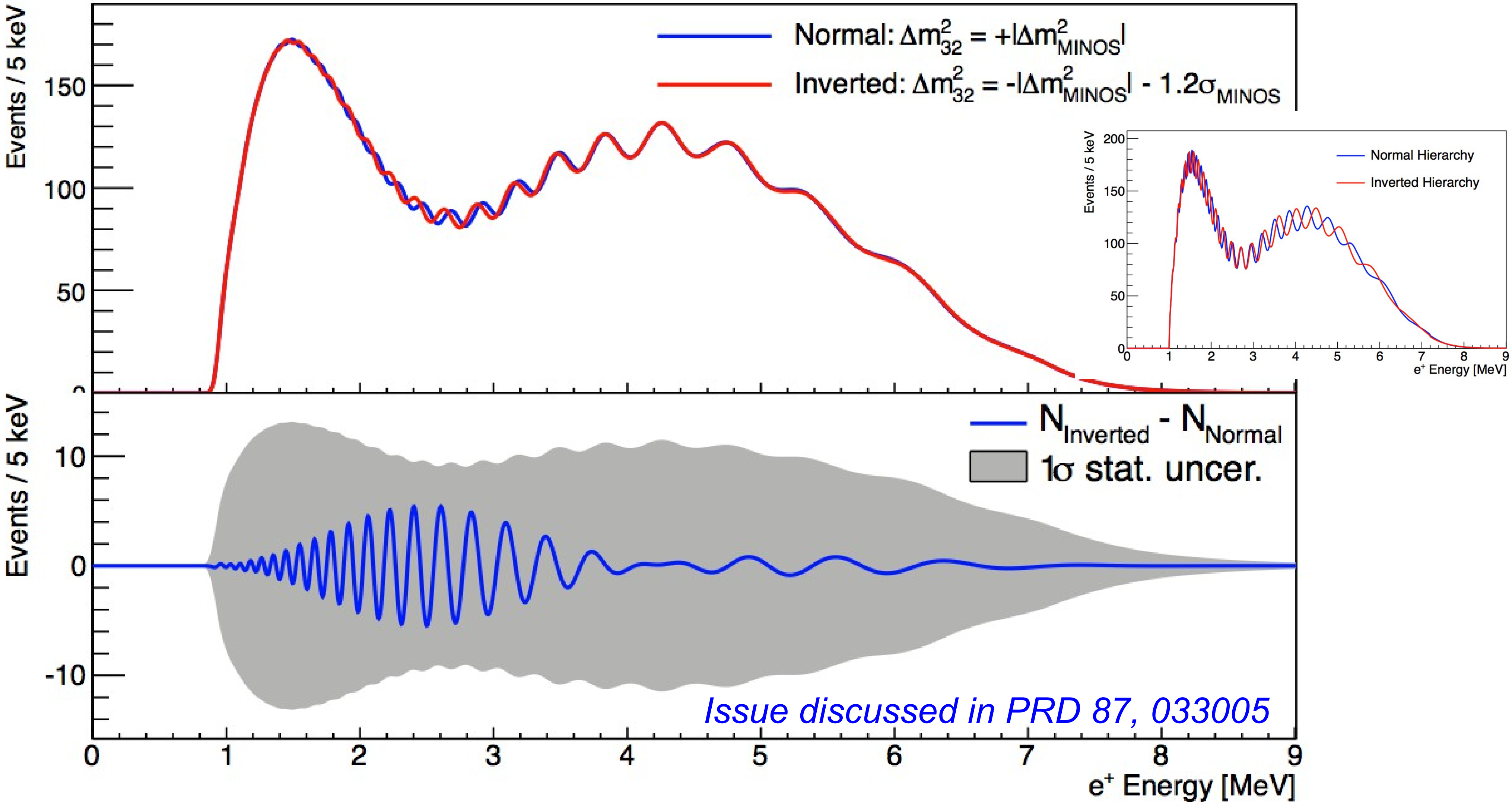
Resolution:

Current state-of-the-art:
~ 6.5% / √E(MeV)
Limited by photo-statistics.

This example:
→ 3% / √E(MeV).

A Diminished Signal

Uncertainty in Δm^2_{MINOS} diminishes sensitivity above ~3 MeV.



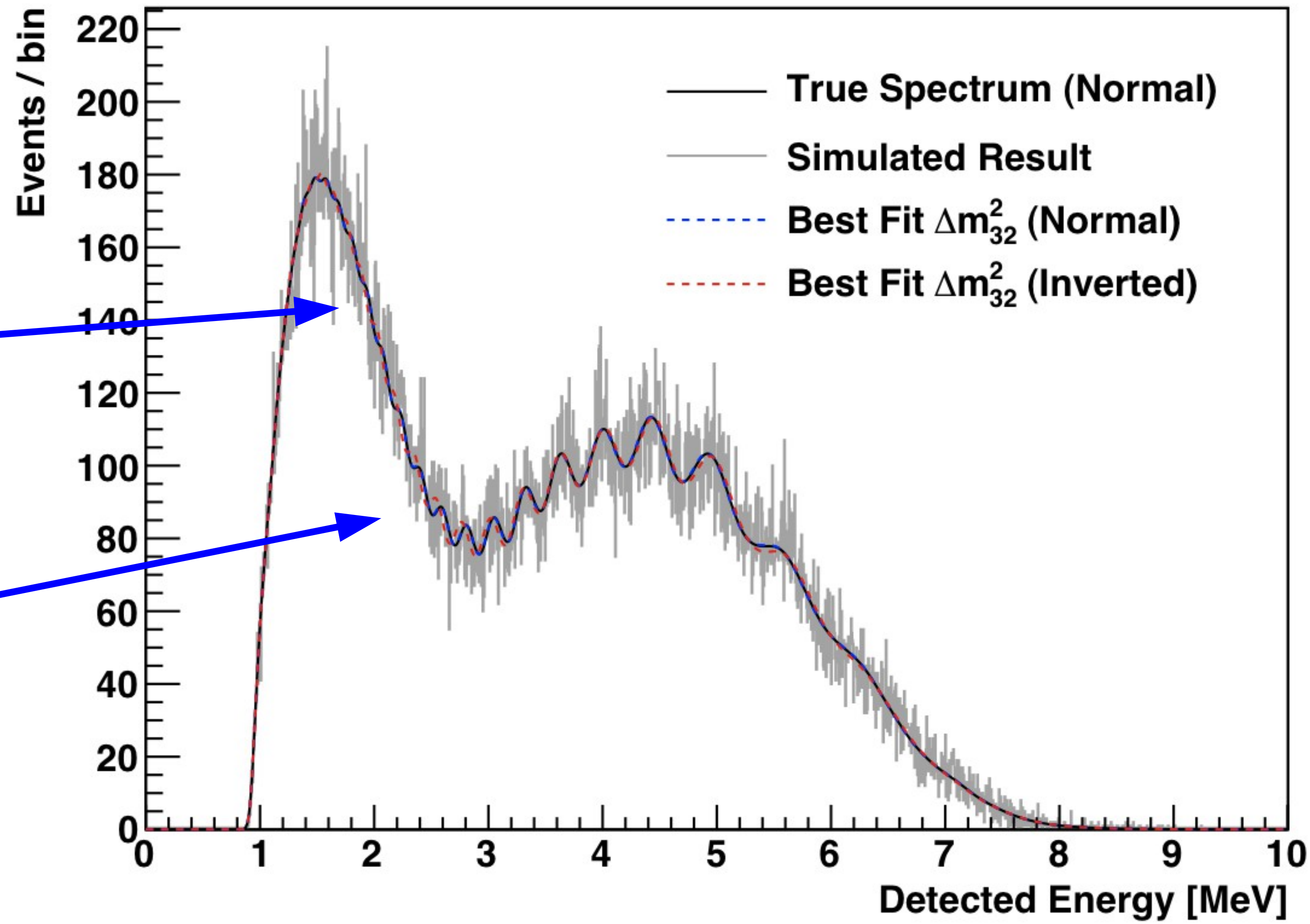
Each bin provides little sensitivity → Fourier analysis methods.

Example 'Experiment' and Fit

Normal and Inverted best fits look almost identical by eye.

Resolution washes out high-frequency oscillation at low energies.

Discrepancy most obvious ~2-3 MeV.

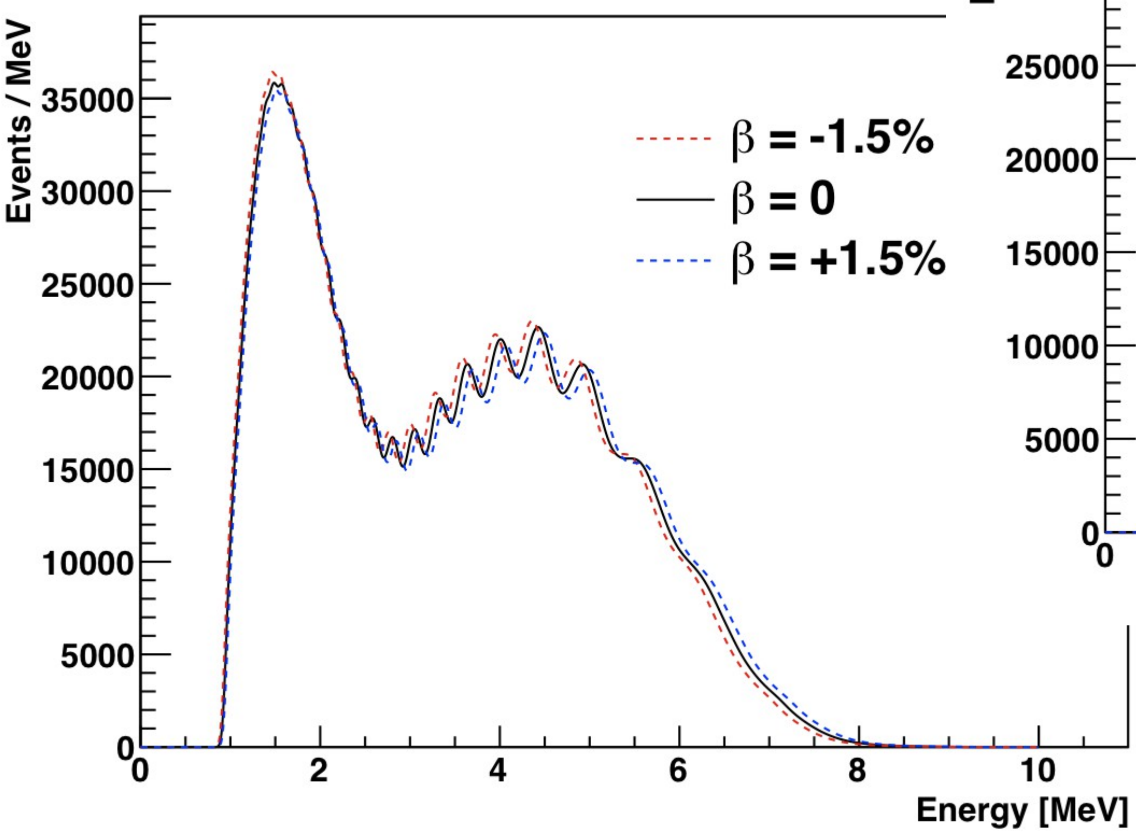


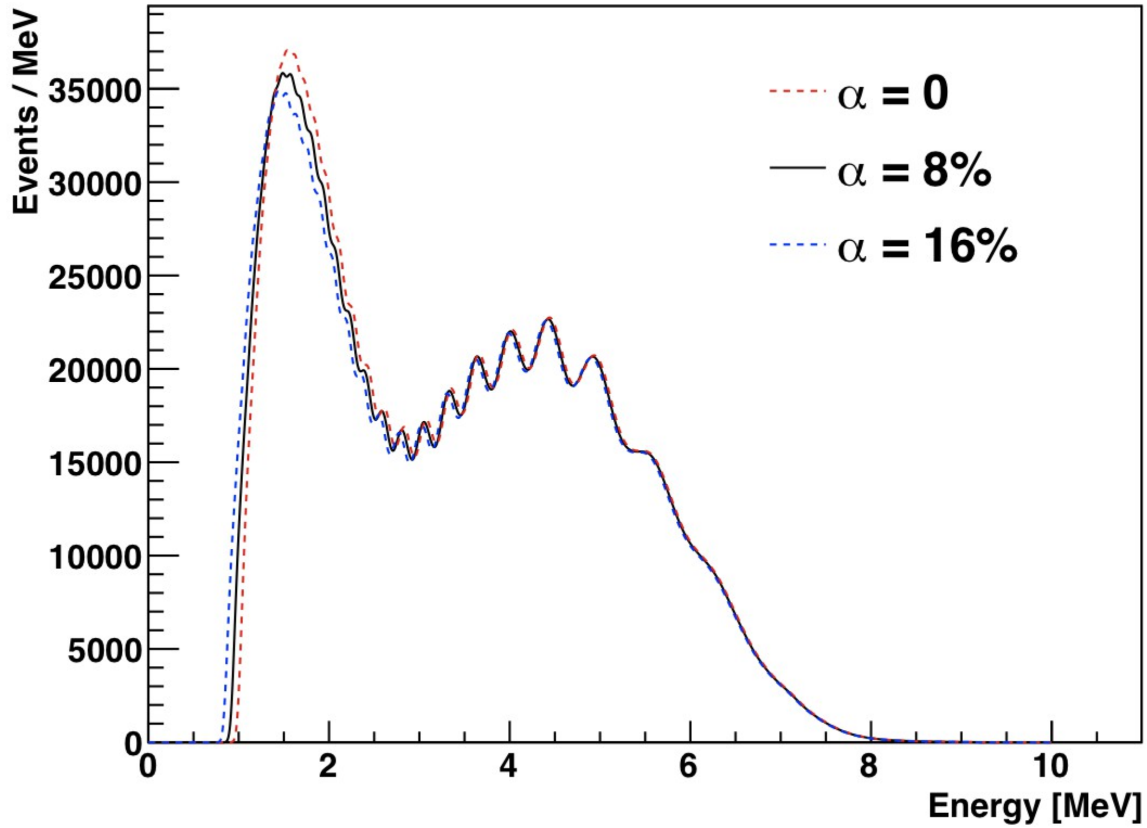
Additional Concerns

Detector calibration and modeling essential for measurement.

Current state-of-the-art allows ~few percent variation in positron calibration.

Consider a linear energy shift.

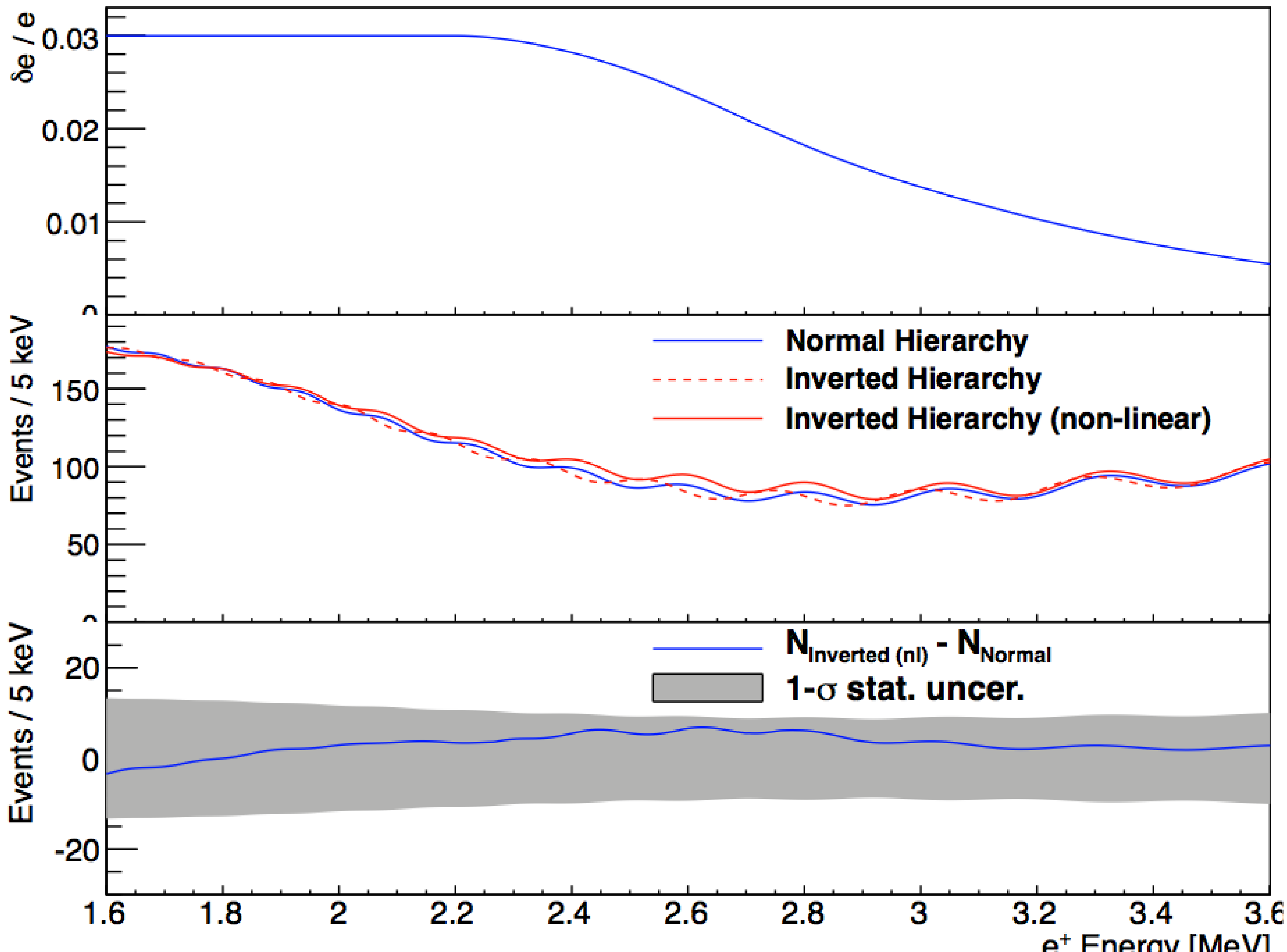




Non-linear scintillator quenching.

'Tuning' the Non-linearity

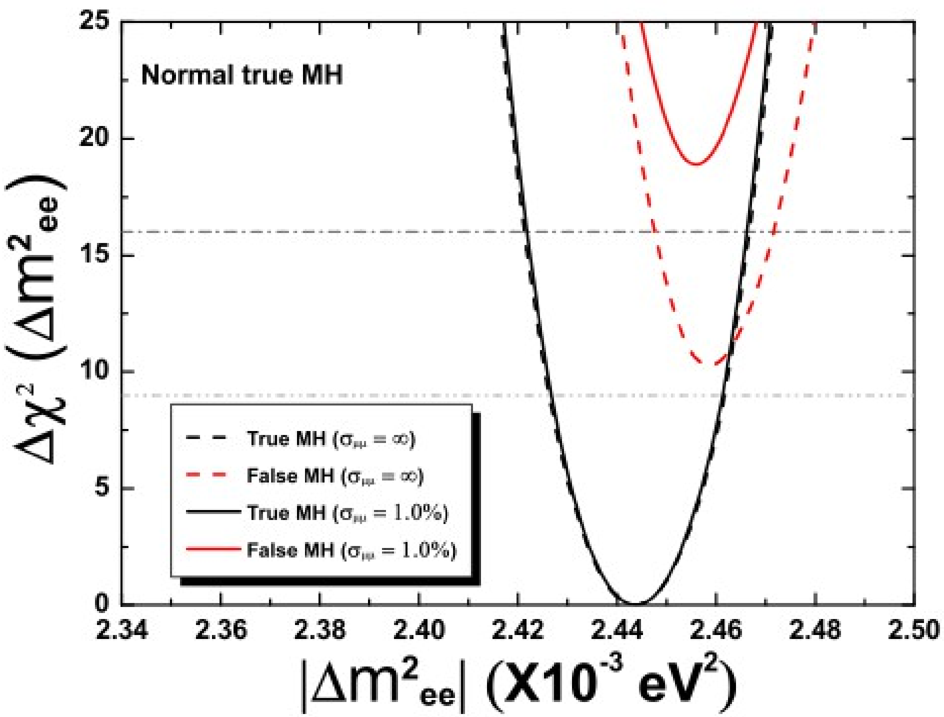
Pathological non-linearity can cause signal to 'vanish'.

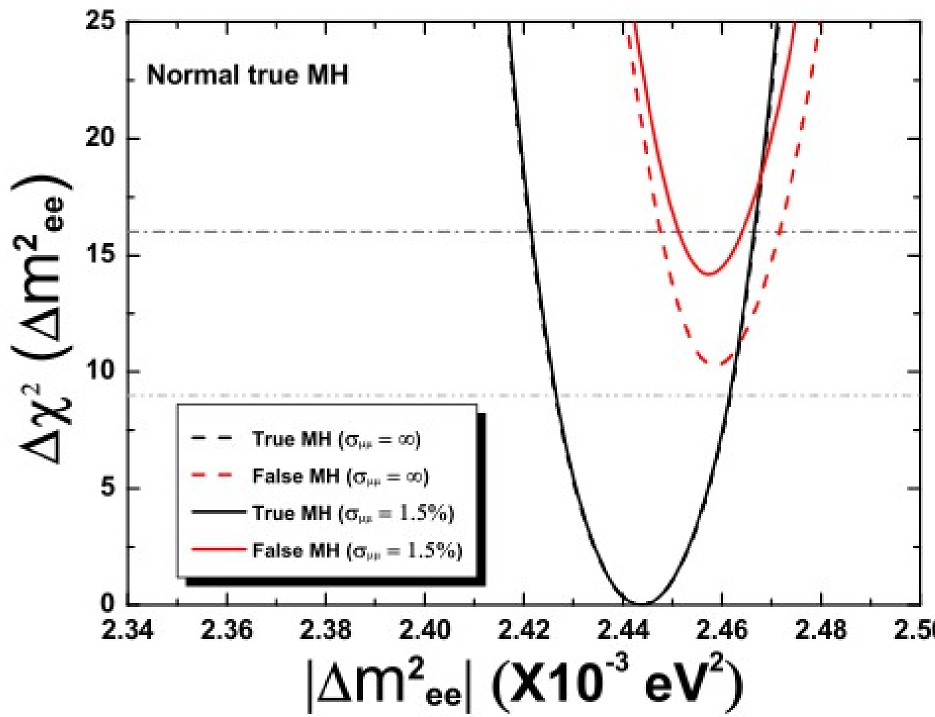


Daya Bay II: Sensitivity

Sensitivity calculation from Daya Bay II: *arXiv:1303.6733*

Assume 5 years data, 3% detector resolution.
Includes actual reactor positions, calibration uncertainty.





1.0% $\Delta m^2_{\mu\mu}$ uncertainty:
→ 4.4σ hierarchy

1.5% $\Delta m^2_{\mu\mu}$ uncertainty:
→ 3.7σ hierarchy

Daya Bay II Status

Schedule is aggressive:

- Already received Chinese equivalent to CD-1 approval
- Civil Construction: 2014-2017
- Detector Assembly: 2018-2019
- Operation: 5-6 years

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Challenges

Some challenges exist for reactor hierarchy measurement:

Uncertainty in Δm^2_{MINOS}:

→ MINOS+, Nova, etc. may reduce uncertainty from 4% to ~2%

Detector resolution:

→ DYB-II goals:

- Maximize PMT coverage (~80%, ~x2.3 KamLAND)
- Increase PMT efficiency (x2.0)
- Increased scintillator light yield (x1.5)
- Increase scintillator attenuation length (16m→30m, x0.9)

Detector Calibration:

→ Calibration of >30m detector to be developed

Reactor cores must be at common distance:

→ Appears that reactor cores ±0.5 km common distance sufficient

Detector structural design:

→ Design for >30m diameter vessel in planning

Summary

Reactor measurement of neutrino mass hierarchy is challenging:

→ Intrinsic signal is marginal due to:
- Uncertainty in oscillation frequency: Δm^2_{MINOS}
- Limited statistics (even for a large 20 kT detector)

→ Technological progress needed to detect 'realistic' signal
- Improved Scintillator, PMT properties needed for >3% resolution.
- Positron calibration required to discriminate hierarchy

Improvements in Δm^2_{MINOS} uncertainty, detector technology would improve prospects.

LBNL Opportunities:

Explore sensitivity dependence on resolution, calibration, etc:

→ A detailed and comprehensive sensitivity study:
Provide clearer guidance and detector requirements.

Participation in Daya Bay II:

→ International contribution likely to be limited.
One specific request is to develop calibration program.